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14. ABSTRACT

This report describes the technical progress towards the development of signed processing algorithms for hybrid lidar- radar designed to improve detection performance.

15. SUBJECT TERMS

Hybrid Lidar - Radar

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MEMORANDUM

Subject: Annual Report
ULI: FY2013

This document provides a annual report on the project "Advanced Digital Signal Processing" covering FY2013.

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William D. Jemison, Professor and Chair, PO Box 5720, Clarkson University, Potsdam, NY 13699-5720
315-268-6509, Fax 315-268-7600, wjemison@clarkson.edu

Award Information

Award Number	N000141110371
Title of Research	Advanced Digital Signal Processing for Hybrid Lidar
Principal Investigator	William D. Jemison
Organization	Clarkson University

Technical Section

Technical Objectives

The technical objective of this project is the development and evaluation of various digital signal processing (DSP) algorithms that will enhance hybrid lidar performance. Practical algorithms must be developed taking into account the underwater propagation channel and the processing requirements for each algorithm as shown in Figure 1.

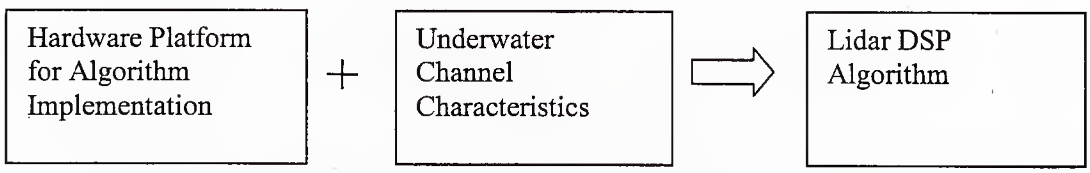

Figure 1. The development of lidar DSP algorithms must take into account hardware implementation and underwater channel characteristics.

Technical Approach

A significant challenge in hybrid lidar-radar is optical absorption and scattering. The absorption of the light photons by the molecules in the water channel contributes to a decrease in the total signal level collected at the receiver. This unwanted phenomenon can be reduced by selecting the wavelength of the laser light to be in the blue-green region. Backscattering occurs when transmitted light signal reflects off a water particulate and reaches the detector without first reaching the object. Thus, backscattered light contains no information regarding the object and it reduces the image contrast and resolution as well as the object ranging measurement accuracy. There have been various methods that attempt to reduce the backscatter. One method is to increase the modulation frequency beyond 100MHz and another is to use a dual high-frequency (>100MHz) approach that uses high speed modulation to help suppress backscatter while also providing an unambiguous range measurement. In general, it is desired to determine which combination of Radio Frequency (RF) modulation frequencies, modulation waveforms, and signal processing algorithms help improve hybrid lidar-radar performance in a variety of underwater environments.

The approach is to focus on the optical proximity detector that is being developed with ONR funding. The goal is to replace analog hardware with digital components to benefit from the advantages offered with digital hardware and signal processing, including better sensitivity due to large dynamic range digitizers and lossless digital demodulation and filtering, reconfigurability via software to improve sensor adaptability in different environments and for multiple applications, and real-time processing for instant feedback.

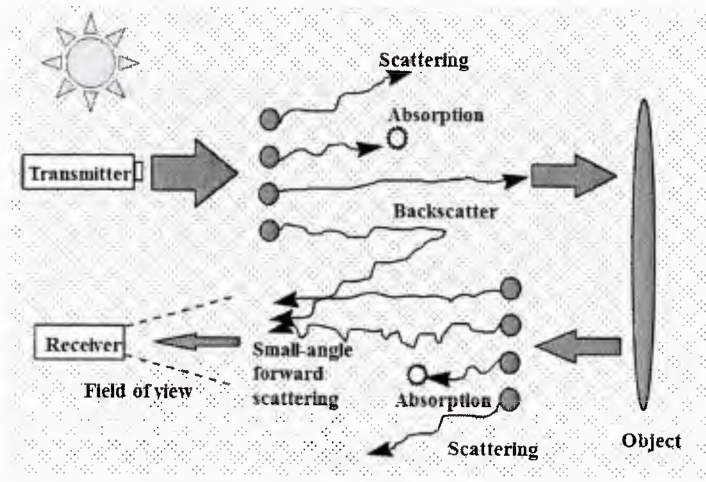

Figure 1. Sketch of water channel effects on hybrid lidar radar system

Although absorption and scattering are two separate physical phenomena, their effects on water conditions are often combined together into a single parameter, the attenuation coefficient c, which has units of m^{-1}. Beam attenuation in water follows an exponential decay law

$$P(c,z) = P_0 e^{-cz}$$

where z is the distance to the object and P_0 is the transmitted signal power. The product cz in the exponent is referred to as the number of attenuation lengths (a.l.), which is a dimensionless parameter used to compare ranging performance in different water conditions and at different distances.

Current Ranging Approaches

This section will briefly discuss two previous ranging approaches developed by Laux et al. [3] that were evaluated in the beginning of this work and serve as a baseline for our work. These approaches both work by modulating the laser and measuring the phase shift between the transmitted and received signals to compute the range. In the single modulation frequency continuous wave hybrid lidar-radar approach (CW), the laser is modulated with a single frequency. As a result, the performance of this method is defined by the wavelength of this modulation frequency.

This results in a number of tradeoffs, which are summarized in Table 1. CW ranging cannot simultaneously achieve high unambiguous range and high range precision. Additionally, there is a tradeoff between unambiguous range and backscatter suppression.

Table 1. Tradeoffs for single frequency CW method

Modulation frequency	Unambiguous range	Range precision	Backscatter suppression
Low	High	Low	Low
High	Low	High	High

The tradeoffs with the single frequency CW approach motivated the Navy to develop the dual frequency approach, in which the ranging performance depends on the difference between the two modulation frequencies. This allows the dual frequency approach to be operated with two modulation frequencies high enough to be above the backscatter cutoff point. This method still has performance tradeoffs to be concerned with, which are summarized in Table 2. As with the single frequency CW approach, there is a tradeoff between high unambiguous range and high range precision.

delay points. It is important to emphasize that the filter response depends on both the spatial delay Δz and the attenuation coefficient c. For example, if the turbidity increases, the filter response will change even when the spatial delay Δz is held constant. This implies that in a practical system the filter would need to be tunable to obtain optimal performance in different turbidities.

Since the spatial filtering approach operates on spatial frequencies rather than the electrical modulation frequency, this causes some potential drawbacks to this method. For a system that only has one photodetector, the platform must somehow be able to track the distance that it has traveled between measurements in order to apply the spatial filter. For systems above water or at shallow depth in calm waters, perhaps this could be achieved with high precision GPS. For systems in areas with strong currents, it would be very unlikely that the system could move an exact distance between measurements without potentially substantial deviations caused by the system drifting in the water. For systems in deep waters, the system will not be able to receiver GPS due to the attenuation of the GPS signal by the water. A submerged platform with two photodetectors at an appropriate spacing avoids this issue but introduces new challenges, primarily that the system size may increase significantly depending on the selected modulation frequency and corresponding optimal delay. Additionally, a system with two photodetectors should ideally place the detectors on an adjustable track so that the system could adapt the detector spacing to changes in modulation frequency or water conditions.

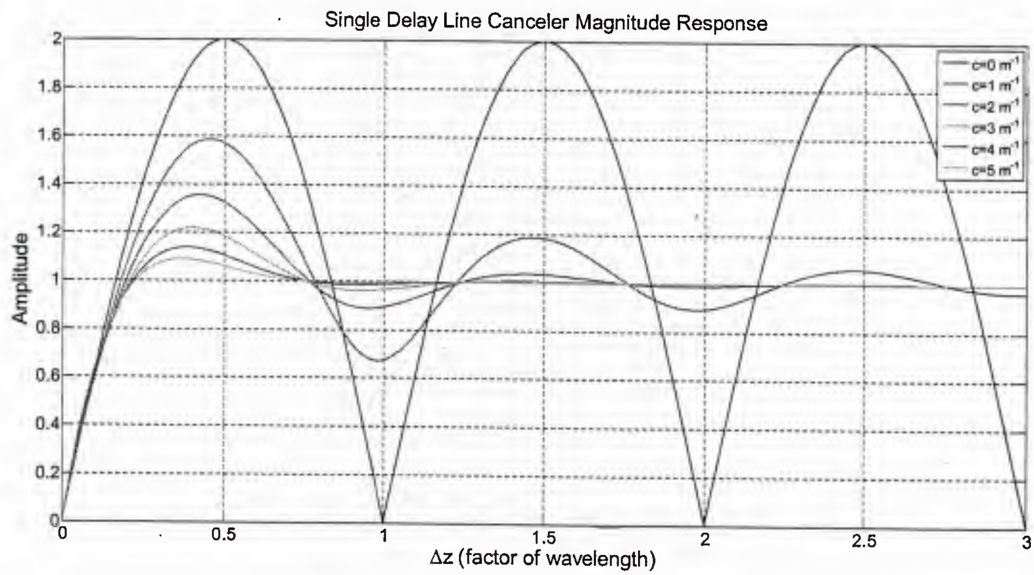

Figure 3. Magnitude response of single delay line canceler

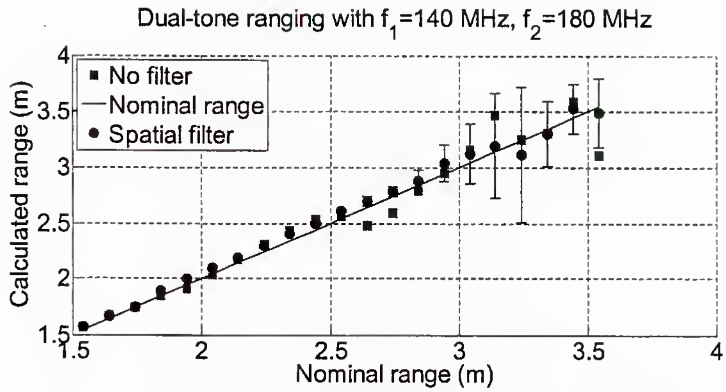

Figure 6. Experimental results for dual frequency CW with spatial filter

Due to the limited range of experimental data set, a set of simulations were run to assess the maximum extent to which each algorithm could range with and without the spatial filter. For the single frequency approach, the spatial filter extended the ranging ability from approximately 7 a.l. to a maximum of 9 a.l., as shown in Figure 7. The dual frequency simulation is shown in Figure 8, where the spatial filter improved the ranging performance by 11.5 a.l. to a maximum of 14.5 a.l. In both Figure 7 and Figure 8, the ranging algorithms begin to provide erroneous range values as they become scatter-limited. These simulations, while extremely promising, do not take into account shot noise limited scenarios and thus represent a best case scenario.

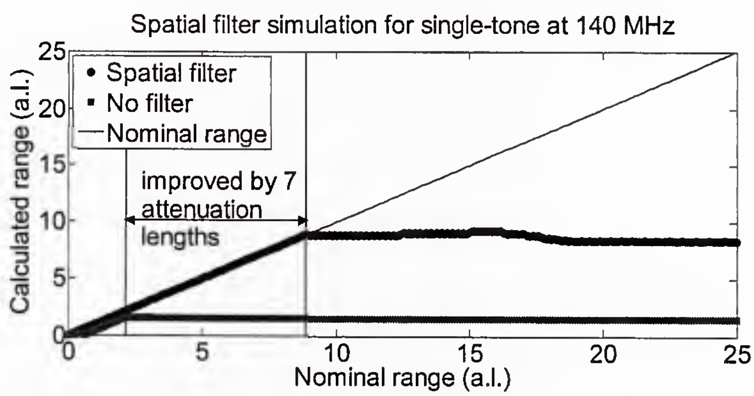

Figure 7. Simulation of theoretical limit on single frequency CW with spatial filter

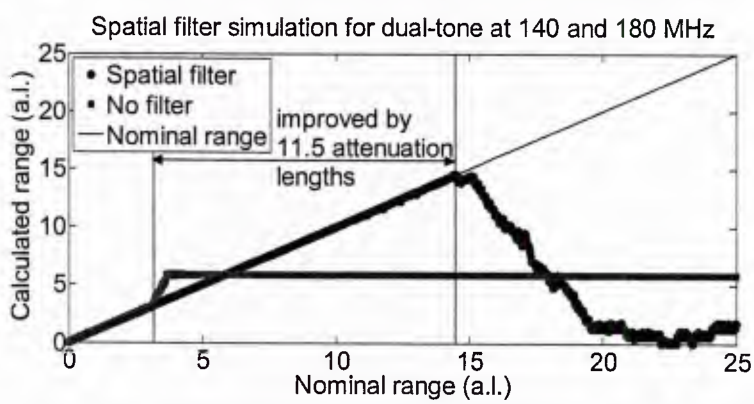

Figure 8. Simulation of theoretical limit on dual frequency CW with spatial filter

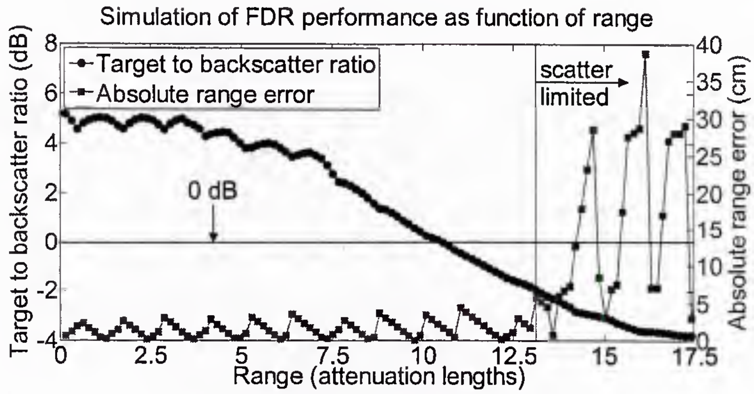

Figure 10. FDR performance vs. turbidity

Blind Signal Separation

For the FDR ranging approach, the statistical signal processing technique of blind signal separation (BSS) was adapted for backscatter reduction. In this technique, data are transformed into a statistical domain in which signals are separated based on their statistical properties [12]. This is analogous to using the Fourier transform to transform data into the frequency domain and separate signals based on their frequency content. Unlike the spatial filtering approach, BSS does not need to be adjusted for every modulation frequency, which made it a much more practical approach for backscatter suppression for the multiple frequencies required in the FDR method. A schematic of the BSS approach is shown below in Figure 11. In the top left, the frequency signal measured by FDR is shown, which contains both backscatter and target information. When this frequency signal is converted to range data, peaks for both the distributed backscatter and the target (correct location indicated with vertical green line) are obtained as shown in the top right. When BSS is applied to the frequency data, the scenario shown in the bottom left occurs, where the backscatter and target signals have been separated. By "zeroing out" the backscatter component, the range plot of the bottom right can be obtained, where the target still shows up in the correct position but the backscatter peak has been reduced by almost 10 dB. The BSS processing steps are critical in developing an automated target detection algorithm, such that the algorithm only detects a single peak instead of being confused by the backscatter return.

Planned work

The majority of the work planned for the immediate future rests upon experimentally verifying the FDR and BSS techniques under a variety of turbidities and practical system configurations which take into account shot noise limited performance. A secondary work objective is to determine how to optimize the necessary processing steps of the new ranging algorithm for use on real-time digital signal processing hardware. In addition, the FDR method will be assessed for possible additional applications due to the instantaneous channel response information that it provides.

Summary of new ranging approach

The new ranging approach developed aims to perform automatic target detection without requiring input from a human operator. In order to achieve unambiguous range and high range precision, the approach requires a wide bandwidth. The dwell time associated with this multi-tone technique also requires additional study. To summarize the major processing steps:

- Frequency-domain reflectometry allows a high unambiguous range measurement of the composite target and backscatter return
- Blind signal separation performs a statistical separation to extract the target return from the composite return signal by essentially filtering out the backscatter return
- Inverse Fourier Transform converts the filtered return signal into an instantaneous range spectrum
- Peak detection detects the range to the target

In scenarios where the FDR sweep is unable to achieve the desired precision due to bandwidth limitations, an optional fifth step can be performed in which a single modulation frequency CW approach may be used to obtain finer precision ranging information following the peak detection step.

Summary

Additional work has been performed to advance the spatial filter work started last year. Improvements on the order of 7 and 11 attenuation lengths are predicted through simulation when spatial filtering is applied to CW and dual-tone ranging, respectively. Application to experimental data showed only modest results; however, the experimental data did not include ranges that were long enough to test the algorithm. The Navy has performed additional experiments to validate the technique.

A new range approach using a combination of frequency-domain reflectometry (FDR) and blind signal separation (BSS) has been developed that allows for automatic target detection at long unambiguous ranges. Frequency-domain reflectometry provides a large unambiguous range independently of the range precision specification. Blind signal separation reduces backscatter in a post-processing fashion without requiring physical modifications to existing systems. Simulations indicate that the new approach can provide a ranging improvement of up to 14 attenuation lengths compared to previous approaches. Experiments are underway to validate the new ranging algorithm and to better understand the tradeoffs associated with dwell time and shot noise limited performance.

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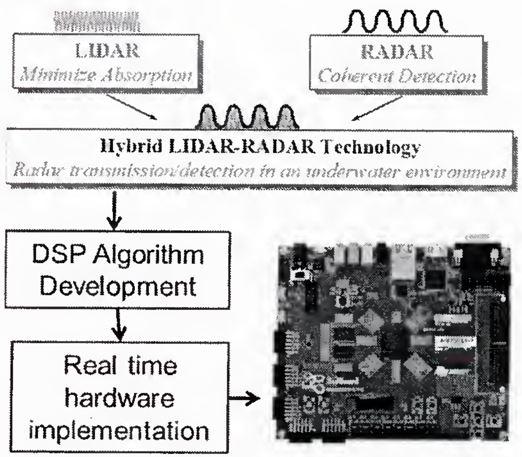
Advanced Digital Signal Processing for Hybrid Lidar N000141110371

Objective:

- Develop and evaluate various digital signal processing (DSP) algorithms that will enhance hybrid lidar performance.

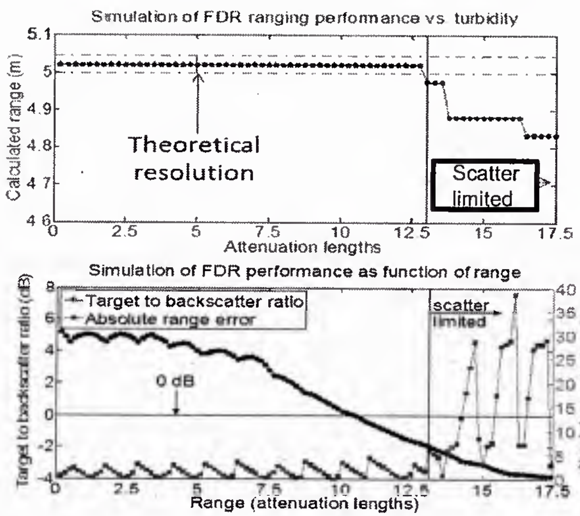


Approach:

- Account for both practical hardware implementation and realistic underwater propagation characteristics
- Leverage existing Navy proximity detection work
- Use a combination of simulated and experimental lidar data to validate algorithms
- Leverage mature signal processing techniques developed for radar and communications to the maximum extent possible

Ranging Algorithm → Backscatter Reduction Algorithm → Automatic Target Detection Algorithm

Figure: A new ranging and backscatter reduction technique have shown that backscatter can be reduced by 10dB and that the correct range can be automatically detected.



Scientific or Naval Impact/ Results:

- Potential performance improvements predicted by simulation are significant
- Validate with more experimentation this year
- Address several practical system issues this year

Ranging Algorithm	Backscatter Reduction Algorithm	Automated Detection Algorithm	Results Achieved via Rangefinder Simulation
Continuous Wave (CW)	Spatial Filter	N/A	Range detection improved by 7 attenuation lengths
Dual Frequency	Spatial Filter	N/A	Range detection improved by 11.5 attenuation lengths
Frequency Domain Reflectometry (FDR)	Blind Signal Separation (BSS)	Peak detection	Backscatter reduced by 10dB and range detection improved over CW by 21 attenuation lengths